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RESEARCH

Investigation of structures' seismic behavior when using the "pendulum column" as an isolator

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Abstract
Isolator systems are among the methods to control the structure's response. Increasing the natural period of structures is one of the methods of strengthening structures against earthquakes, which are usually supplied with seismic isolators. In the present paper, a suspended isolation system called the "pendulum column" is investigated. In this system, by changing the structure's foundation connection, the period of the structure has been increased. The proposed isolator system was investigated under different earthquake records. The results showed that the proposed isolator had effectively reduced the acceleration due to its isolation. Among the different damping ratios, those with ratios of more than 15% had better results. The results of the ABAQUS model verified the theory. The results showed that the system's acceleration was effectively reduced. Investigations showed that the base shear in the isolated structure decreased by more than 50% in the investigated earthquakes. The drift decreased by more than 50% in all analyses. An experimental sample of the proposed system confirmed the proper functioning of the pendulum column.

Keywords Isolator · Pendulum column · Earthquake · Damping · ABAQUS · MATLAB

Introduction

The occurrence of earthquakes has always caused a lot of financial losses and deaths throughout human history (Farahmand et al., 2022). Appropriate methods have been proposed and devised to prevent earthquake damage. The techniques have been used to strengthen structures against earthquakes. Some of them have become more common, such as installing bracing members in frames, moment-resisting frames, and shear walls (Takeuchi et al., 2015). Most of these methods are based on the fact that the earthquake force is transmitted through the foundation to the structure; then the force is distributed among the particular elements that are placed in the structure for this purpose. It is assumed that the earthquake force is withstood by these elements. However, the structure is completely affected by earthquake force in these methods. Despite the fact that these structures are used to deal with earthquakes, the severity of the earthquake can cause severe damage to such structures. If the structure is to be resistant to this type of earthquake, then materials with higher resistance and more formability should be used, which would result in excessive cost. Among the other methods for controlling the response of structures is the use of isolation systems that act without increasing the strength of structures by minimizing the resonance problem by significantly changing the fundamental frequency of the structure (Avinash et al., 2022). The main objective of a seismic isolation method is to prevent the direct transfer of the earthquake force from the foundation to the structure. Base isolation as a powerful technology can reduce the seismic response of the structure and prevent damage to the structure (Chen et al., 2014). Seismic isolation causes the acceleration—exerted by earth motion—on the structure to decrease as the natural period lengthens.

Some monuments in Pasargadae, the capital city of ancient Persia, which date back at least 2500 years, have lasted without seismic damage to date. In those historical buildings in Iran, which is one of the most seismically active

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regions of the world, multi-layer stones have been utilized as a construction method. The surfaces of those large stones are smoothed and flat. It is said that they have been made to have less friction during an earthquake's excitation and are able to move back and forth over the lower foundation without damage.

Seismic isolation technology has advanced significantly in the modern era. Kelly (1986) provided extensive reviews on historical developments and literature on the isolation of the base by 1986. Barghian and Shahabi (2007) proposed mushroom-shaped base isolation for the first time, and later it was tested in a lab by Lu and Hsu (2013a, 2013b). Wei et al., (2017, 2018a, 2018b) investigated the rolling base isolation with concave and convex friction distribution. They found that the concavely distributed friction force changed the natural period of the structure. In other research, Wei et al., (2018a, 2018b) studied the scaling of the P–F isolation system for shaking table model tests. Karayel et al. (2017) proposed spring tube braces for building seismic isolation, in which the first story columns were erected as two ends pinned as a soft story mechanism. Losanno et al. (2019) proposed a polyester fiber-reinforced rubber with a low cost of construction and implementation.They utilized polyester fiber instead of carbon fiber in the proposed system because it had a lower cost while achieving comparable seismic performance. Calabrese et al. (2019) conducted laboratory tests on recycled rubber—fiber-reinforced bearings (RR-FRBs). They studied the seismic behavior of the isolator under some earthquakes. They obtained the essential parameters for analytical modeling. Chen and Xiong (2022) proposed an improved base-isolation device composed of conventional friction pendulum bearing (FPB) and viscous damper (VD) to achieve seismically resilient design of structures during earthquakes. The results showed that, in comparison with the prototype system without any isolation approach and with conventional FPB, the proposed FPB-VD device was quite efficient in reducing both the structural acceleration and deformation demands. Ali et al. (2022) researched five distinct low-cost isolation layer materials that are locally available and used in sliding base-isolation systems. They observed a reduction of 40–53% in acceleration response at the top floor level on an isolated model compared to the fixed-based model. Chen et al. (2022) suggested the use of a base-isolation system that utilized lead rubber bearing with negative stiffness springs (LRB-NS). This system comprises conventional lead rubber bearings (LRBs) and pre-compressed springs installed at the base of bridge columns. The research findings indicated that the LRB-NS mechanism could be effectively designed to reduce seismic demands on bridge columns while also being highly efficient in limiting excessive deformation in the bearings, which was often observed in traditional LRB systems during strong excitations. Sadeghi Movahhed et al. (2023) aimed to evaluate the impact of varied Ground Motion (GM) sets, which includes Far-Fault (FF) and Near-Fault (NF) records, on the seismic response of triple friction pendulum (TFP) isolated structures. The study findings indicated that the damage energy exerted on the superstructure under NF records with forward-directivity pulses (NF-FD-GMs) was more significant than damping energy when using the initial design parameters' values (IDPVs) of the isolator. Conversely, other GM sets showed an inverse trend. Dong et al. (2023) have suggested a three-dimensional (3D) isolation device comprising of a conventional horizontal bearing as well as a recently developed long-period vertical isolation

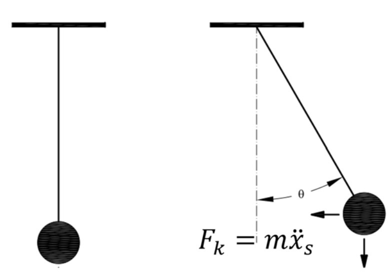

Fig. 1 Simple pendulum

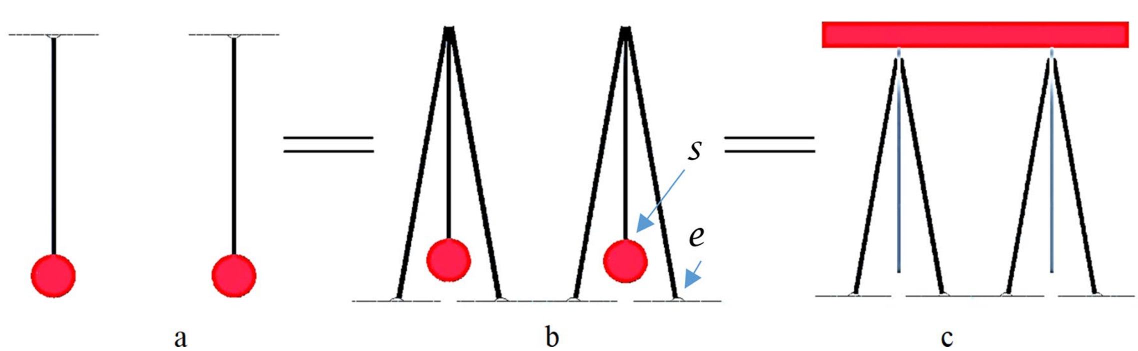

Fig. 2 Equalizing a pendulum system with an isolator system

device that has variable stiffness (LVIVS). Cimellaro et al. (2020) presented a three-dimensional (3D) base-isolation system designed to control both the horizontal and vertical components of ground motion. The system adopted a negative stiffness device (NSD), which functioned as an adaptive passive protection system capable of altering the stiffness of the structure. Numerical analyses demonstrated that the inclusion of NSDs reduced the vertical acceleration within the structure. However, the relative displacements increased. Consequently, it was deemed advisable to introduce additional damping measures to mitigate this effect. De Domenico et al. (2020) proposed an efficient base-isolation system that combined low-friction curved surface sliders (CSSs) with hysteretic gap dampers. The latter device would introduce additional energy dissipation only when the displacement of the isolation system exceeded a threshold or initial gap, remaining disengaged otherwise. The mechanical properties of the gap damper were designed to achieve target energy dissipation, ensuring that the displacement demand of low-friction CSSs matched that of high-friction CSSs. The proposed base-isolation system effectively integrated satisfactory energy dissipation, reducing the displacement demand, and high re-centering capability, leading to minimal residual displacements. Beirami Shahabi et al. () investigated a system of seismic isolation for buildings—called SCSI in which the building columns were placed on the hinged cradle seats instead of having direct connection to the foundation. The numerical and experimental results confirmed the effectiveness of the proposed isolation method

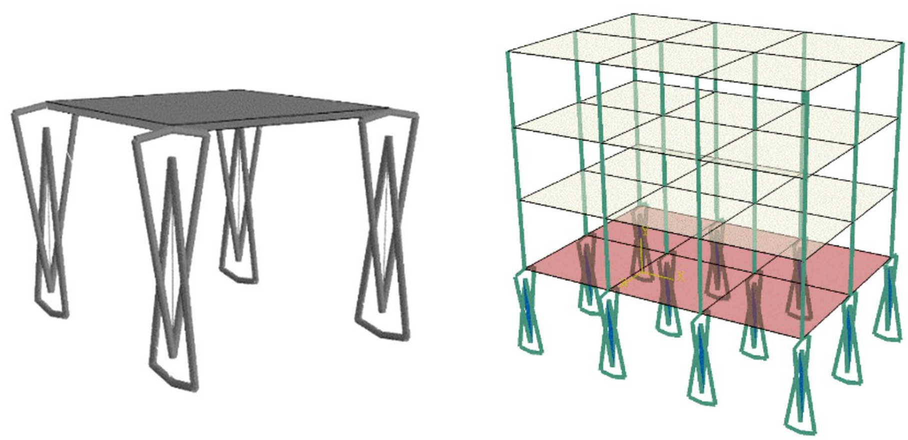

Fig. 3 A schematic 3D picture of the system located under the structure (Azizi & Barghian, 2023a)

Table 1 Earthquakes information

Earthquake	Time	Source	Recording station	PGA (g)
Chi-chi (Taiwan)	September 20, 1999	PEER Strong Motion database	TCU045	0.36
Friuli (Italy)	May 06, 1976	PEER Strong Motion Database	TOLMEZZO (000)	0.35
Hollister (USA)	April 09, 1961	PEER Strong Motion Database	USGS STATION 1028	0.2

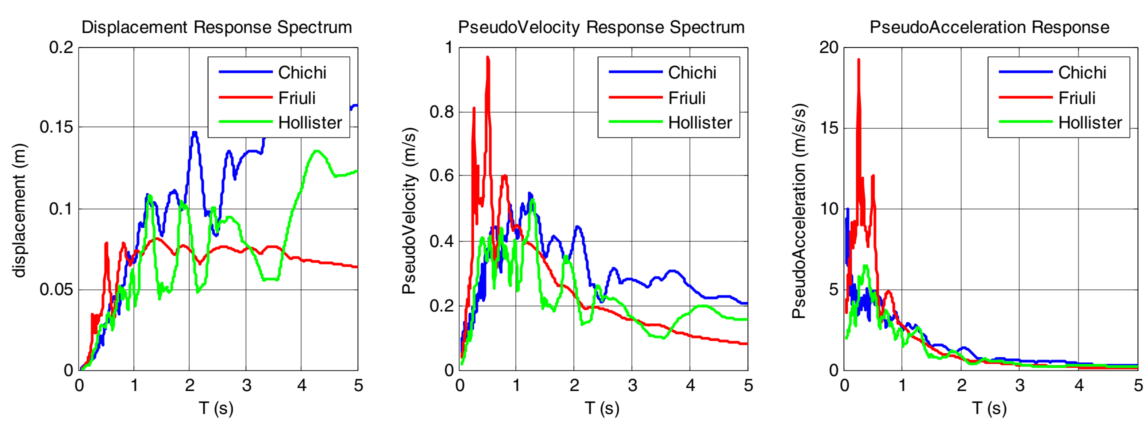

Fig. 4 Earthquakes response spectra-damping ratio = 2%

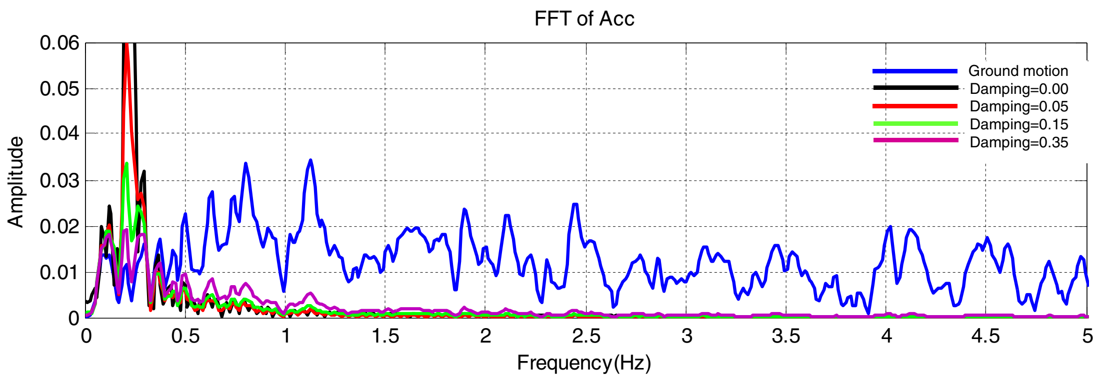

Fig. 5 FFT analyses of Chichi earthquake

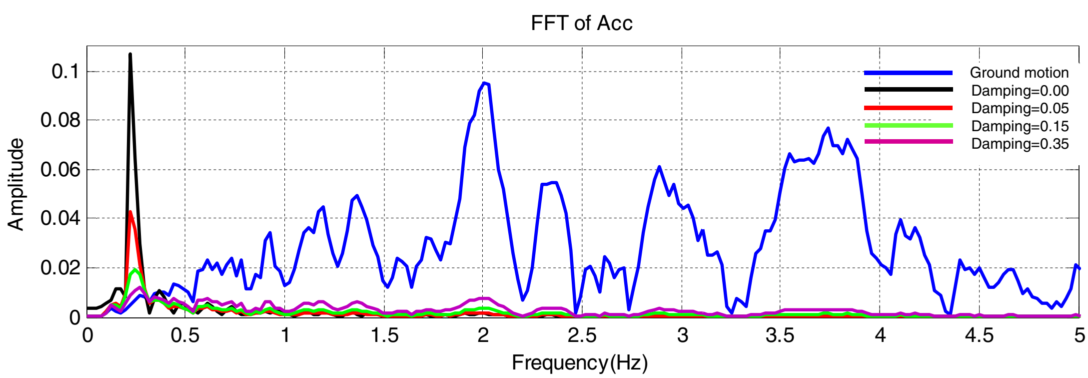

Fig. 6 FFT analyses of Friuli earthquake

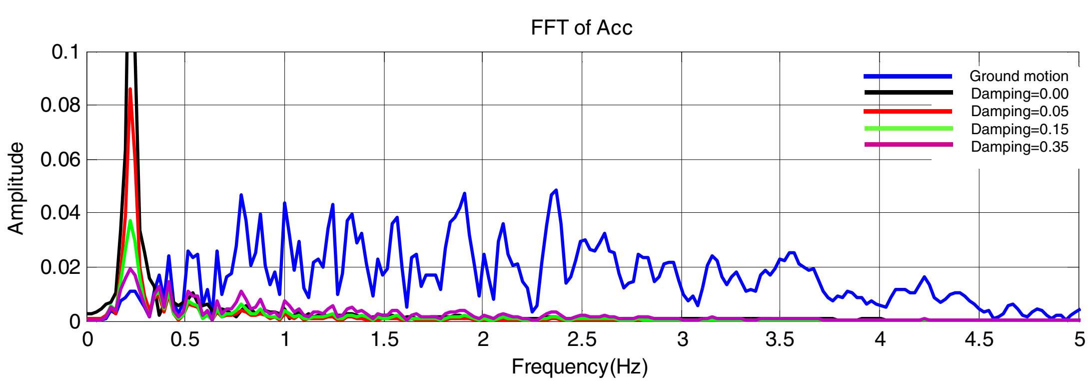

Fig. 7 FFT analyses of Hollister earthquake

in reducing the seismic effects on the structure. In another paper, Beirami Shahabi et al. (2020b) categorized the methods of seismic isolation based on their mechanisms. They discussed the advantages and disadvantages of those methods.

Almost all the methods proposed have disadvantages and advantages. For instance, the high cost of LRB isolators, the possibility of welding at the sliding surface in friction isolators, and the stress concentration problem in rolling isolators. Therefore, it is necessary to continue the research to improve the performance of isolators. In this research, a simple implementation mechanism is investigated called a pendulum column for seismic isolation in structures. It acts as a mass-independent mechanism like FPS isolation, but without permanent displacement. This method has almost all the capabilities of a suitable isolator, and in this system,

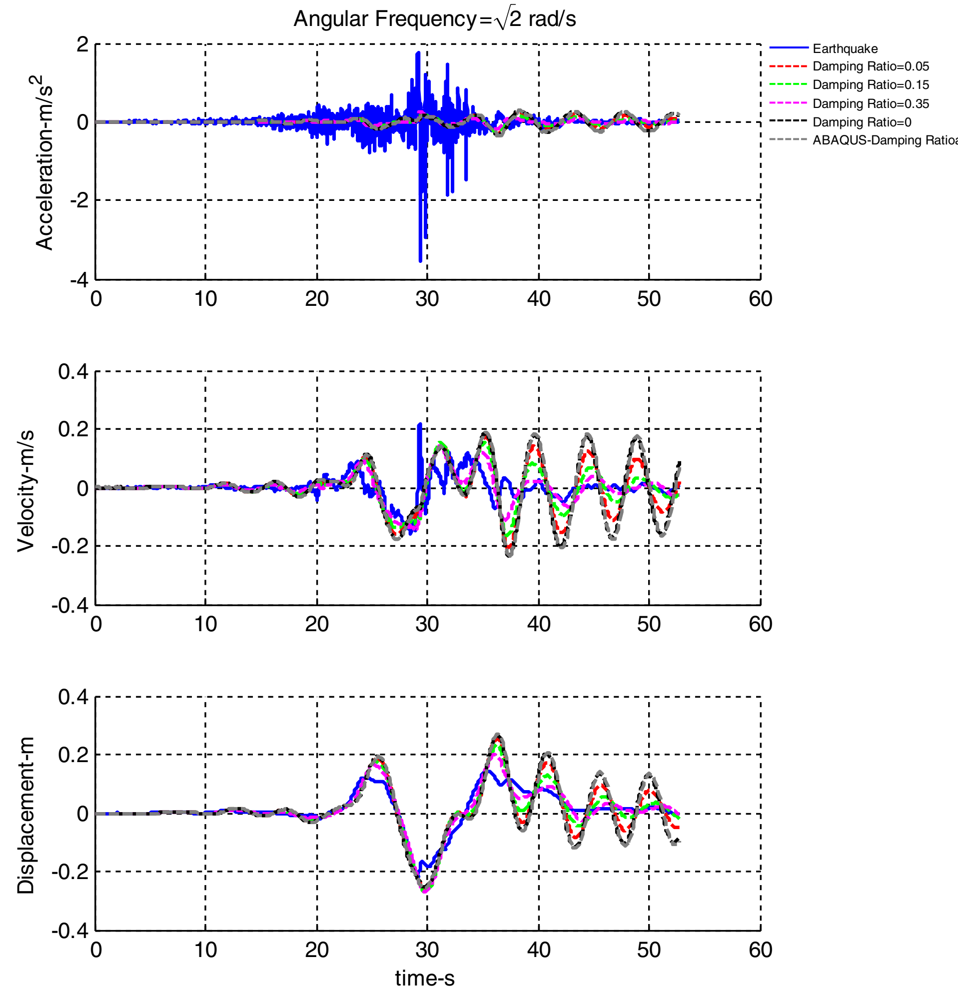

Fig. 8 The isolator response to the Chi-chi earthquake for different damping ratios

many of the disadvantages of common isolators have been significantly eliminated. In this method, the structure is connected to the foundation in the form of a pendulum in order to prevent the transfer of strong ground acceleration to the structure.

Increasing the natural period of structures is one of the methods of strengthening structures against earthquakes, which are usually supplied with seismic isolators. In present research, by changing the structure's foundation connection, the period of the structure has been increased.

The equations of the proposed model

To explain the proposed model, a pendulum is considered (Fig. 1). When the pendulum's weight deviates from its original location, it returns to its original point after several oscillations due to gravity. If the upper part of the pendulum (the support) moves instead of the mass in the horizontal direction, acceleration is applied to the weight to balance the forces.

For earthquake-like movements, the acceleration of the pendulum weight is much less than the acceleration of the upper part of the pendulum. Figure 2 depicts the used concept from this point of view. Figure 2a, b shows the pendulum and equalized systems, respectively. System 2c, in which two ∨-shaped elements are hung from the support (ceiling) and are connected to the ^-shaped elements by a straight rod, can be used in place of system 2b. Because of the 2D plane, the ∨-shaped elements are perpendicular to the shown plane and appear as two vertical rods.

The ∨ element transfers a part of the upper structure's weight to the bottom section through the vertical rod, which acts as a pendulum rod. The proposed system is placed under the structure. Figure 3 shows a 3D view of this method. As is seen in Fig. 3, the ∨ and ∧ elements are perpendicular to each other and are connected to each other by a two-ended hinged rod. The ceiling is hung by the ∨ elements. The system equations can be derived based on the assumptions made in Fig. 3. Since the isolator is equivalent to a pendulum, the equations are written for the pendulum. In the following equations, the letters "e" and "s" refer to the earth and the structure mass,

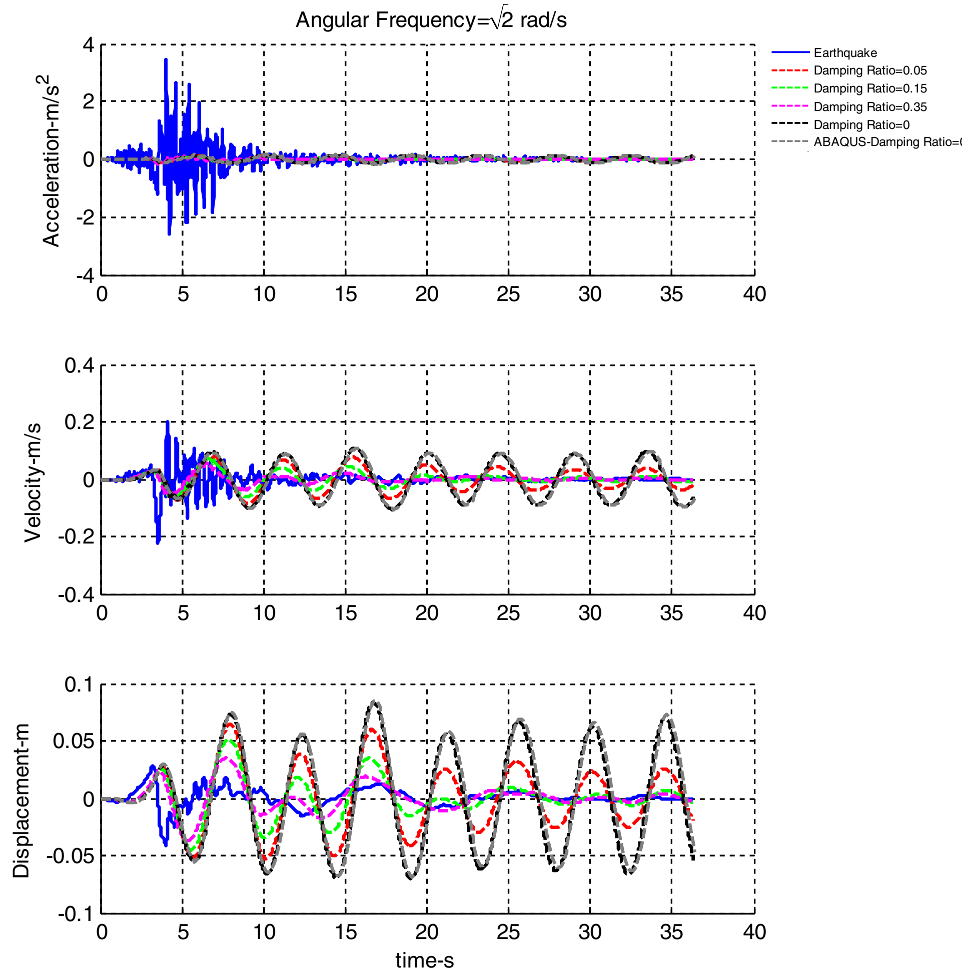

Fig. 9 The isolator response to the Friuli earthquake for different damping ratios

respectively. The earth's movement and the lower part of the pendulum are displayed by x_e and x_s, respectively. In this case, an angle is created in the rod (shown in Fig. 1), which causes the force to be applied to the weight.

This force is equal to

$$F_k = m\ddot{x}_s = -mg\frac{\left(x_s - x_e\right)}{l}. \tag{1}$$

where m, g, and l are mass, ground acceleration, and pendulum length, respectively.

$$m\ddot{x}_s = mg\frac{\left(x_e - x_s\right)}{l}. \tag{2}$$

By arranging Eq. (2), it can be written as Eq. (3):

$$m\ddot{x}_s + m\frac{g}{l}x_s = m\frac{g}{l}x_e. \tag{3}$$

The damping force can be written as

$$F_D = C\left(\dot{x}_e - \dot{x}_s\right). \tag{4}$$

By adding Eq. (4) to Eq. (3), the general equation of motion for the system is obtained:

$$m\ddot{x}_s + C\dot{x}_s + m\frac{g}{l}x_s = m\frac{g}{l}x_e + C\dot{x}_e. \tag{5}$$

The isolator response to earthquakes

To investigate isolator response in some earthquakes, the pendulum column is initially considered a one-degree freedom system. Because of the mass-independent property of the pendulum column, almost all the typical structure responses can be predicted before designing (Azizi & Barghian, 2023b). Considering the pendulum length to be 5 m and the damping ratios to be 0.5, 15, and 35%, results, including movement responses and FFT analysis of acceleration, are given.

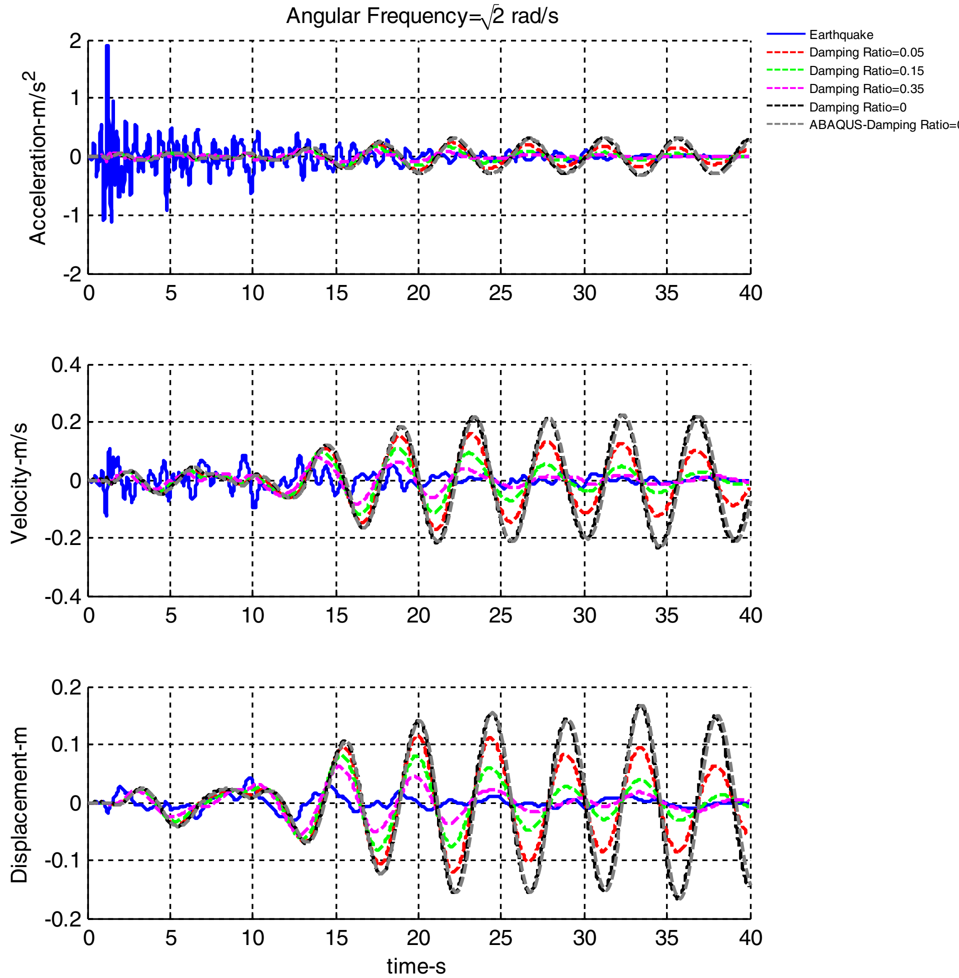

Fig. 10 The isolator response to the Hollister earthquake for different damping ratios

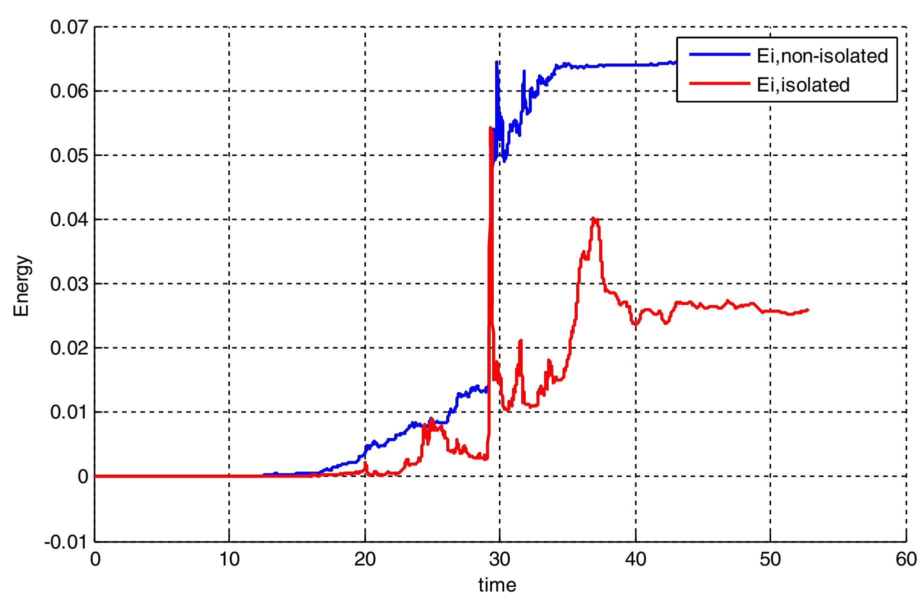

Fig. 11 The input energy comparison—Chi-chi earthquake

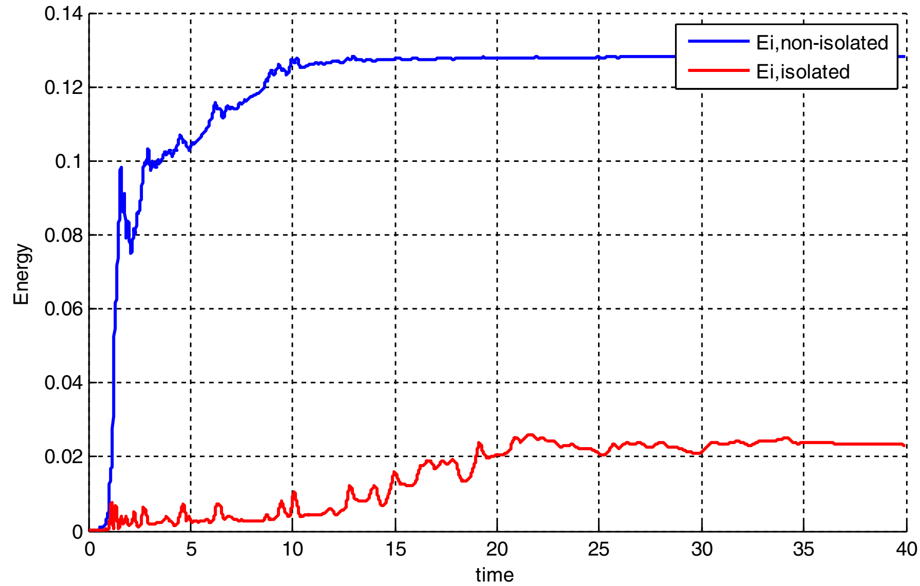

Fig. 12 The input energy comparison-Friuli earthquake

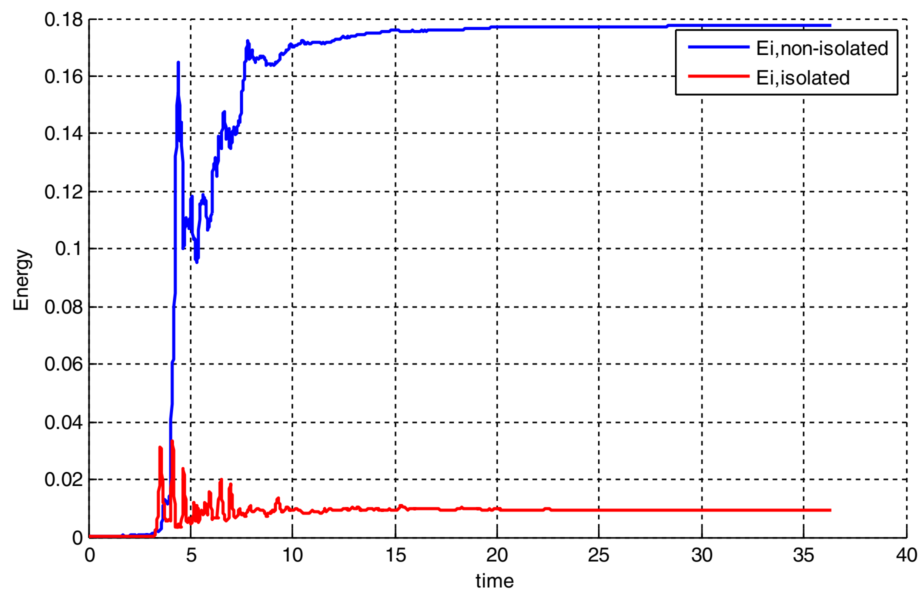

Fig. 13 The input energy comparison—Hollister earthquake

The isolator response diagrams for chosen earthquakes were obtained and plotted in Figs. 5, 6, 7, 8, 9 and 10. For comparing ABAQUS and MATLAB results, the damping ratio of 0% for each is plotted.

Earthquakes pieces of information are given in Table 1 and Fig. 4.

The fast Fourier transform is a convenient way to investigate waves. This method shows the frequency components of the waves in a weighted (amplitude) and continuous form. Therefore, by comparing the fast Fourier transform of the vibration caused by the ground motion with the response of the isolated structure, the weighted changes of the frequencies in the ground motion can be observed. In other words, the fast Fourier transform shows the function of the isolator in the proper way of filtering the short-range frequencies and the impact, which is the main factor in the destruction of structures.

The results show that the presence of the damper reduces the relative displacement of the structure from the ground, but at the same time, it increases the acceleration

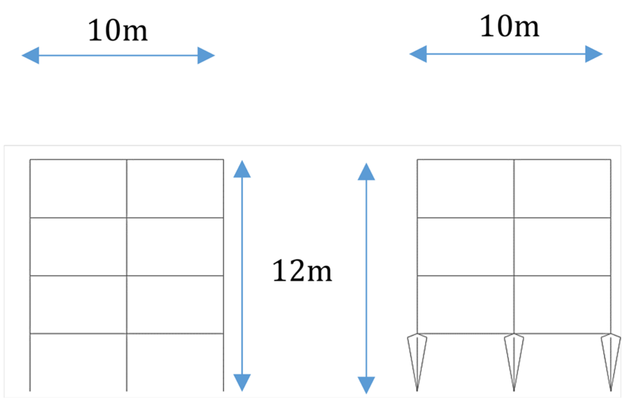

Fig. 14 4-story frame modeled by ABAQUS

of the structure. However, this increase in acceleration is negligible compared to the amount of reduction that occurred in the displacement. Also, the damper has eliminated the accelerations caused by the oscillations that remain in the structure after the earthquake peak has passed. The velocity graph is not broken, and the displacement graph is quite mild. In both velocity and displacement graphs, the impact of vibration has been filtered, which makes the residents feel more secure during the earthquake.

Figures 5, 6 and 7 show that a significant part of the short-range and impulse frequencies are filtered by the isolated system. The diagrams show that the resonance problem can be controlled using a suitable damper. According to Eq. 5 and considering that conventional structures have appropriate rigidity, assuming a one-degree-of-freedom system and examining the general behavior of isolated structures, the graphs shown in Figs. 8, 9 and 10 are shown. Graphs show that the response acceleration of the isolated system is significantly reduced.

The amount of energy transferred to the structure or the work done by the earthquake is a suitable criterion for evaluating the performance of the seismic isolator. This criterion indicates the energy absorbed by the internal members of the structure. The analysis of the structure from the point of view of energy can be investigated in two ways: absolute energy or relative energy.

In this research, relative energy relationships were used. An isolated structure of a single degree of freedom with the mentioned specifications was compared to a non-isolated structure with a periodicity of 0.4 and an inherent damping of 5 percent.

From the point of view of incoming energy, Figs. 11, 12 and 13 show that under the vibrations of the earth, this system reduces the incoming energy to a great extent.

The velocity and displacement diagram shows the soft behavior of the isolated system against ground vibration, which brings a sense of safety to the residents. The stated content shows the movement behavior of isolated systems. To check the safety performance of isolated structures, it is necessary to check the internal parameters and the forces created inside the isolated structure. To investigate pendulum column functionality in structures, a 4-story model with and without an isolator was designed in ABAQUS. The shape of the building, profile, and load properties are shown in Fig. 14 and Table 2.

Base shear and drift can give good feedback on the performance of isolated structures. In Fig. 15, the drift of the last story and the base shear of the middle column are shown. More than a 50% reduction in base shear and drift can indicate the proper performance of the proposed isoater. Figure 15 depicts the middle column base shear and end story drift.

Experimental test

An experimental model was built and tested. The model consisted of four piers, and each pier was a pendulum column. The height of each pendulum column was 50 cm, and two plates were used (instead of ceiling and floor). The dimensions of the plates were 40 cm by 60 cm. Then, the model was mounted on a shaking table at Tabriz University. Figure 16 shows the model tested in the lab. A sine displacement was applied on the system instead of load pattern. Different frequencies were used. Results showed that the horizontal displacements of the upper plate related to base plate were reduced by about 80%. Figure 17 shows two frames of the video taken in the lab. As it is seen in Fig. 17, the columns are faded because of the intensity of movement, while the upper part has remained stationary.

The response of the structure against periodic loads is according to Tables 3 and Fig. 18.

Table 2 Structure profiles and load property

Beam	Load	Column S1	Column S2, 3	Column S4
Rigid $L=5$ m	4800 kg/m as mass	Box 0.2×0.2 $h=3$ m $t=1$ cm	Box 0.18×0.18 $h=3$ m $t=1$ cm	Box 0.16×0.16 $h=3$ m $t=1$ cm

L length of beams, *h* height of columns, *t* thickness of boxes, and *S* stories

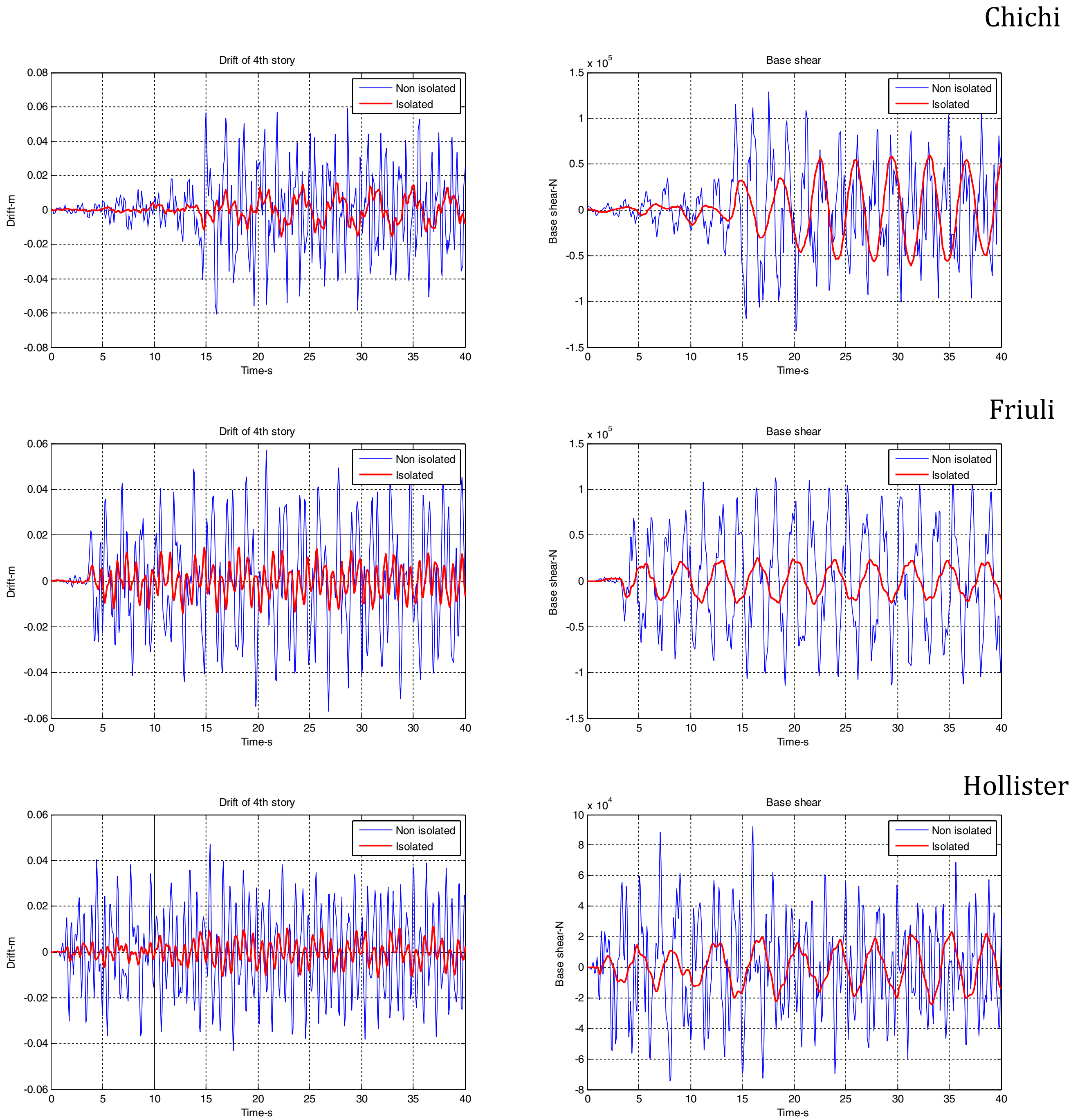

Fig. 15 Base shear and end story drift

Conclusions

Increasing the natural period of structures is one of the methods of strengthening structures against earthquakes, which are usually supplied with seismic isolators. In this paper, by changing the structure's foundation connection, the period of the structure has been increased. Three different earthquake records were chosen, and then three different damping ratios were used. According to the equations derived from this research, the mass parameter has been removed from the main equations. Therefore, by assuming a system of one degree of freedom, structures

Fig. 16 The tested model

with sufficient rigidity can have similar seismic behavior during vibration; mass independence gives a perspective on a structure's behavior during earthquakes. The results showed that the proposed isolator had effectively reduced the acceleration due to its isolation. Among the different damping ratios, those with ratios of more than 15% had better results. The results of the ABAQUS model verified the theory.

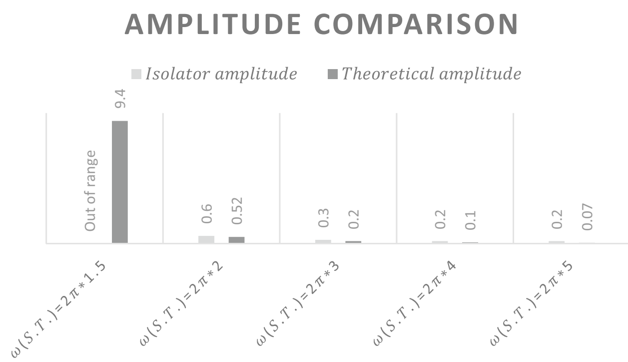

Fig. 18 Comparison of the maximum displacements of the structure in teorical and experimental analyses

The input energy analysis showed that the input energy to the isolated structure was lower than the non-isolated structure in all analyses. FFT analysis of the acceleration response shows that vibrations are reduced in the main domain of frequency and the resonance is controlled by applying a suitable damper. To check the performance of the pendulum column, a four-story structure was modeled in the ABAQUS software. Investigations showed that the base shear in the isolated structure decreased by more than 50% in all earthquakes. The drift decreased by more than 50% in all analyses. The experimental sample confirmed the proper functioning of the pendulum column.

Fig. 17 Two captured frames of a video

Table 3 The maximum displacements of the structure against periodic loads

Natural ω = 5.7 S.T. amplitude = 2 cm	ω(S.T.) = 2π	ω(S.T.) = $2\pi \times 2$	ω(S.T.) = $2\pi \times 3$	ω(S.T.) = $2\pi \times 4$	ω(S.T.) = $2\pi \times 5$
Isolator amplitude	Out of range	0.6 cm	0.3 cm	0.2 cm	0.2 cm
T*h*eoretical amplitude	9.4 cm	0.52 cm	0.2 cm	0.1 cm	0.07 cm

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Declarations

Conflict of interests The authors declare no competing interests.

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